

APPARATUS AND METHOD FOR MEASURING CONCENTRATIONS OF
SCALE-FORMING IONS

Field of Invention

This invention relates to the determination of ion concentrations in downhole water from hydrocarbon wells, aquifers etc. This is useful in a wide range of applications, including predicting the formation of scale and fingerprinting waters from different sources.

Background

10 The prediction of the location and type of mineral scale that may form around or within the production or surface facilities of an oil well is an important factor both in the design of the well and the formulation of strategies to cope with the mineral scale.

15 Current methods for predicting mineral scale formation involve the retrieval of samples from downhole, which are then either analysed at the surface or else sent off to laboratories for analysis. Errors and delays can arise
20 from this *ex situ* analysis.

Electrochemical methods have previously been developed for the measurement of the concentration of a number of different metal ions, and some have been deployed in shallow boreholes, lakes and ocean waters. However, the application of these methods to oilfield operations has been limited, as the high temperatures (up to 175 Celsius) and pressures (up to 1500 bar) common to most reservoirs, make their use impractical. Furthermore, many electrochemical methods are not able to distinguish between the principal metal ions (Ca^{2+} , Ba^{2+} and Sr^{2+}) responsible for scale formation. This problem is compounded by the low concentrations of these ions

(about 10s mg/L) in formation water which is often highly saline.

The ability to rapidly and conveniently distinguish
5 scaling ions may also find application, for example, in
fingerprinting waters flowing into a hydrocarbon well
from different producing zones. This information, which
is indicative of connectivity between different zones of
a producing well, may allow the optimization of
10 production strategies for recovering the oil in place.

Summary of the Invention

An object of the invention is to provide improved methods
for the measurement of the scaling ions, which are
suitable for use *in situ* i.e. in a continuous connection
15 to a flow of fluid.

Accordingly, a first aspect of the invention provides an
apparatus for determining the concentration of scaling
ions in downhole water; the apparatus comprising a ligand
20 which binds scaling ions from a flowing fluid, which
could be downhole water, said ligand having an electronic
configuration which is altered on binding of a scaling
ion, and a detector for determining alterations in said
electronic configuration, the amount of said alterations
25 being indicative of the concentration of the scaling ion
in the sample.

Preferably the ligand is contained within an
electrochemical cell and changes in the electroactivity
30 of the ligand are determined, for example
amperometrically or voltammetrically. In other
embodiments, the binding of a scaling ion may alter the
fluorescent properties of the ligand. Changes in the

fluorescence of the ligand upon binding of the ligand may be determined using any of a range of conventional techniques.

5 The apparatus may comprise a single ligand which binds specifically to a single scaling ion, such that changes in the electronic configuration of the ligand are directly related to the concentration of the scaling ion in the sample water.

10

More preferably, the apparatus may contain two or more different ligands, for example three, four, or five or more. Alterations in the electronic configuration of each ligand may be determined independently, either

15 simultaneously or sequentially.

In some embodiments, each ligand may bind specifically to a different scaling ion. Changes in the electronic configuration of each ligand are directly related to the

20 concentration of the corresponding scaling ion in the sample water.

In other embodiments, each ligand may bind to two or more different scaling ions. Changes in the properties (i.e.

25 the electronic configuration) of each ligand are directly related to the concentration in the sample water of the two or more scaling ions to which that ligand binds. The different electronic response of the ligand to different ions can be translated into a respective concentration

30 measurements, for example by locating the peaks in a voltogram.

Alternatively, each ligand may bind to a different combination of scaling ions such that the concentration of each individual scaling ion in the sample water may be calculated from the measurements determined for two or
5 more different ligands.

An advantage of the apparatus is that it allows *in situ* analysis to be performed, thereby avoiding the problems associated with transporting samples to the surface for
10 *ex situ* analysis. The present invention is partly based on the realisation that electrochemical techniques can be adapted for performance downhole, i.e. in relatively demanding and hostile conditions.

15 Preferably the detector is operably connected to a processor for determining the concentration of scaling ions from the current or potential in the cell.

In some embodiments, the apparatus is adapted for use
20 downhole (i.e. in a hydrocarbon well or aquifer).

The processor may also be adapted for use downhole, or alternatively it may be intended for remote installation e.g. at the surface. For example, the processor may be a
25 suitably programmed computer.

A further aspect of the invention provides for the use of apparatus as described herein for *in situ* measurement of scaling ion concentration.

30 In another aspect the invention provides a method of monitoring the concentrations of scaling ions in downhole water comprising;

contacting a sample of downhole water with a ligand which selectively binds scaling ions, wherein the binding of scaling ions in said sample to the ligand alters the electronic configuration of the ligand;

5 measuring changes in the electronic configuration of the ligand; and,

determining the concentration of said scaling ion from said changes in electronic configuration.

Brief Description of the Figures

10 Specific embodiments of the invention will now be described with reference to the following drawings, in which:

Figures 1A and 1B show examples of an apparatus according
15 to the invention.

Figures 2 to 5 show examples of ligands suitable for use in accordance with the invention.

20 Figure 6 shows a voltogram measured using a ligand of figure 5 in an ion-free fluid and a fluid with Ba-ions.

Figure 7 shows a flow diagram of a method in accordance with an example of the present invention.

25 Figure 8 shows an example of a scale sensor in a downhole application.

Detailed Description of the Invention

30 In general terms, the present invention relates to the measurement of concentration of ions in downhole water, in particular ions responsible for scale formation by means of changes in the electronic configuration of a

- ligand which binds scaling ions. A preferred approach involves the use of an electrochemical cell containing a ligand whose electroactivity changes on binding a scaling ion. Changes in ligand electroactivity upon ion binding
5. alter the electrochemical properties of the cell and may be measured using a detector. Other approaches may comprise the use of a ligand whose fluorescent properties change on binding of a scaling ion.
- 10 Downhole water may be comprised within a production fluid from a hydrocarbon well or reservoir, which may comprise hydrocarbons, drilling mud etc. The downhole water may, for example, be connate water.
- 15 Scaling ions are ions which are responsible for the formation of scale. The principal scaling ions in downhole water are Ca^{2+} , Ba^{2+} and Sr^{2+} . A suitable ligand may bind selectively to one or more of these scaling ions e.g. a ligand may bind to Ca^{2+} , Ba^{2+} and Sr^{2+} . Preferably,
- 20 a ligand shows substantially no binding to other ions.

In some embodiments, the ligand may have a different binding affinity for each of the three principal scaling ions (Ca^{2+} , Ba^{2+} and Sr^{2+}), allowing the levels of each individual ion in the downhole water to be determined.

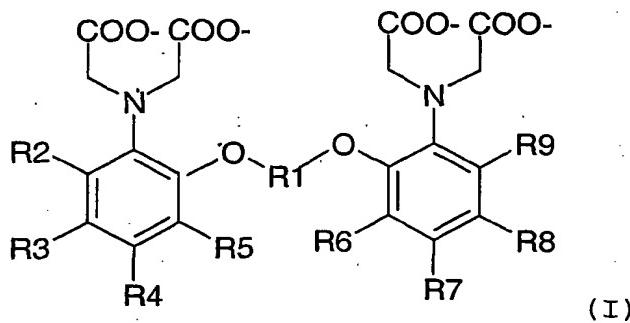
25 Discrimination between different ligands may be achieved, for example, by determining the characteristic redox properties of each ligand at different potentials.

30 The ligand may be present in the cell in an aqueous solution at a concentration of 0.1 to 10mM, preferably 1 to 10mM, or may be dispersed within a porous polymer membrane.

Ligands suitable for use in accordance with the invention are stable and able to bind scaling ions under downhole conditions, for example at high temperature (e.g. up to 175°C) and pressure (e.g. up to 1500 bar).

5

One class of suitable ligands have the formula (I):



10 where R1 is a C₁₋₅ alkyl (including, e.g. unsubstituted C₁₋₅alkyl and substituted C₁₋₅ alkyl) or C₁₋₈ aryl (including, e.g. unsubstituted C₁₋₈ aryl and substituted C₁₋₈ aryl); and,

15 R2 to R9 may independently be H, halogen (F, Cl, Br, I); C₁₋₅ alkyl group; O-C₁₋₅ alkyl group; COOH; NH₂; -CONH₂; CO-C₁₋₅ alkyl group; or a fluorophore group such as carboxy-X-rhodamine (ROX), tetramethylrhodamine (TAMRA) and fluorescein (FAM).

20 "C₁₋₅ alkyl" pertains to a monovalent moiety obtained by removing a hydrogen atom from a C₁₋₅ hydrocarbon compound having from 1 to 5 carbon atoms, which may be aliphatic or alicyclic, or a combination thereof, and which may be saturated, partially unsaturated, or fully unsaturated.

25 Examples of suitable ligands according to formula I are shown in Figure 2.

In some embodiments, the aromatic rings of suitable ligands may comprise substitutions in the ortho, meta or para positions (i.e. at one or more of positions R₂ to R₉), in order to shift the redox features of a ligand to 5 allow scanning for the different ions in well-separated spectral windows, in order to prevent interference.

For the purpose of this invention the above class of ligands are referred to as O,O'-Bis(2-aminophenyl) 10 ethyleneglycol-N,N,N',N'-tetraacetic acid or BAPTA derivatives.

Other suitable ligands may include cryptands (Lehn & Sauvage (1975) J. Am. Chem. Soc. 97 23 6700), for example 15 a ligand shown in Figure 3, and thymolphthalein and their derivatives (Qing and Yuying (1987) Talanta 34 6 555), for example ligands shown in Figure 4. Other suitable ligands may include neutral ionophores (Simon et al Anal. Chem. 1985, 57, 2756), specific crown ethers (D.J. Cram 20 et al J. Am. Chem. Soc., 1973, 95, 3021) or antibiotics such as valinomycin.

A further ligand of the cryptand family is shown in figure 5. The cryptand is derivatized by a redox-active 25 group or moiety M. The entity M can be selected for example from a group consisting of Fe, Ru, Co, V, Cr, Mo, and W and n and m can range from 1 to 3.

For the purpose of this invention, ligands of the type of 30 figure 3 and 5 are referred to as cryptand derivatives.

The apparatus may further comprise a porous membrane or porous electrode block which allows ions within the downhole water to pass into the cell to contact the

ligand. A suitable porous membrane may be made of zeolite or a ceramic material. A block may be made of epoxy material as base material.

- 5 The membrane may be contacted with discrete samples or batches of downhole water or the membrane may be contacted with a continuous flow of downhole water. The apparatus may comprise one or more liquid guidance channels to direct downhole water to the membrane and to
10 remove downhole water after contact with the membrane.

The detector may comprise one or more electrodes which contact the ligand. Various arrangements of electrodes may be used as is conventional in electrochemistry.

- 15 Conveniently a three-electrode arrangement consisting of a working electrode, a reference electrode and a counter electrode may be used. Preferably, the working electrode is composed of a material resistant to fouling, such as
20 boron-doped diamond or glassy carbon, the counter electrode is platinum and the reference electrode is Ag/AgCl. Other suitable electrode materials, such as AgI, are known to those skilled in the art.

- 25 The electrodes may be used to detect changes in the electroactivity of the one or more ligands. For example, electroactivity changes caused by the presence of scaling ions may alter the current flow or voltage between electrodes. Current or voltage may be detected or
30 measured by the detector. For example, the potential of the electrodes may be varied and the current measured or vice versa. The current or potential difference associated with the electroactivity of each of the one or more ligands may be measured by the detector and

correlated with the concentration of scaling ions in the downhole water sample. In the presence of the target ions, the peak current(s) should increase, proportional to the concentration of the target species. A power source may be connected to the electrodes to drive the current between the electrodes. The power source may be an integral part of the apparatus, and, for example, may be comprised within the detector. In other embodiments, the power source may be separate from the apparatus and connectable thereto. The apparatus may comprise appropriate circuitry for connection to the power source.

The ligand may be contained within the apparatus in any of a number of ways. In some embodiments, the ligand may be dispersed in an aqueous solution within a chamber of the apparatus. In other embodiments, the ligand may be dispersed within a porous polymer membrane. Binding of the scaling ions by the ligand occurs within the pores of the membrane and resultant changes in current or potential are detected by circuitry connected directly to the membrane via the working, counter and reference electrodes. The use of a porous membrane is convenient in allowing the miniaturisation of the voltammetric or amperometric sensor, thus leading to faster response times, lower consumption of reagents and lower unit costs.

In other embodiments, the ligands may be attached to conducting solid particles, such as carbon or a metal (e.g., gold), which are incorporated into the surface of one or more of the electrodes, preferably, the working electrode. The accumulation of particles with attached ligand forms a conducting porous electrode with ligand attached to the walls of the pores. Suitable techniques

for fixing the particles to the electrode surface include epoxy resin adhesion or abrasive immobilisation. A porous electrode for hydrogen sulfide determination, for example, is described in co-pending published United 5 Kingdom application GB-A-2391314.

For example, the ligand (I) above may be designed such that group R8 is an amine (-NH₂), which can be reacted with nitrous acid to form the diazonium ion -N⁺=N and 10 subsequently coupled to carbon particles by reduction of the diazonium group by hypophosphorous acid. The ligand is thus chemically bonded to the carbon particles and these can be incorporated into the working electrode 4 as described above. In other embodiments, the ligand (I) 15 above may be coupled to gold particles with one of the groups R2 to R9 being either an amine (-NH₂) or a thiol (-SH).

As described above, the detector may be operably 20 connected to a processor that determines the concentration of scaling ions in the sample from the current or potential difference measured by the detector. The processor may be separate from or part of the detector. The processor may also be adapted for use under 25 downhole conditions (i.e. high temperature, high pressure and high salinity). Alternatively, it may be intended for remote installation e.g. at the surface. For example, the processor may be a suitably programmed computer.

30 The measurement of scaling ion concentrations as described herein may be useful in downhole sampling, production logging to characterise flow into the well, and thereby aid remediation or production strategies, and in permanent monitoring applications, where the build up

of scale or water breakthrough/flooding of the reservoir might be gauged.

Figure 1A shows a cross-sectional diagram of an apparatus according to one embodiment of the invention. The apparatus is shown separated into an upper and a lower part as in a stage of being assembled. Inlets 11 and outlets 12 for sampling downhole water are indicated by arrows pointing in the direction of the flow. The sample water contacts a membrane 13A which allows the passage of ions into the cell 14. The ligand solution in the cell 14 is contacted by a Ag/AgCl reference electrode 15, a platinum ring counter electrode 16 and a glassy carbon working electrode 17. The electrodes 15, 16 and 17 detect changes in the electroactivity of ligand in the cell 14 which are related to scaling ion concentration.

In the variant of figure 1B, a scale sensor 20 is shown coupled to a flowline 23. The body 21 of the sensor is fixed into the end section of an opening 22. The body carries a microporous epoxy matrix 211 embedding the catalysts 214 and contacts 212 that provide connection points to voltage supply and measurement through a small channel 221 at the bottom of the opening 22. A sealing ring 213 protects the contact points and electronics from the wellbore fluid that passes under operation conditions through the sample channel 23.

In an example according to an embodiment of the invention, the four ligands (2A-2D) shown in Figure 2 may be present in solution in cell 14 or embedded in block 211.

These ligands have different binding properties; ligand 2A binds Ca^{2+} , Sr^{2+} and Ba^{2+} ; ligand 2B binds Ca^{2+} and Sr^{2+} , ligand 2C binds Sr^{2+} and Ba^{2+} and ligand 2D binds Ba^{2+} .

- 5 The level of Sr^{2+} in the sample water may be determined, for example, by measuring the alterations of the electroactivities of ligands 2C and 2D in the cell and then subtracting the value obtained for ligand 2D from value obtained for ligand 2C, to provide a value which
10 represents the concentration of Sr^{2+} . (i.e. $2\text{C} - 2\text{D} = [\text{Sr}^{2+}]$). As above the figure label is taken as a representative of the respective ligand and/or the concentration measurement associated with it.
- 15 The level of Ca^{2+} in the sample water may be determined by measuring the alterations of the electroactivities of ligands 2B, 2C and 2D in the cell. The values for ligands 2B and 2D are added together and the value obtained for ligand 2C is subtracted from this combined figure, to
20 provide a value which represents the concentration of Ca^{2+} . (i.e. $2\text{B} + 2\text{D} - 2\text{C} = [\text{Ca}^{2+}]$).

The level of Ba^{2+} in the sample water is determined by measuring the alterations of the electroactivities of
25 ligands 2A and 2B in the cell and then subtracting the value obtained for ligand 2B from the value obtained for ligand 2A, to provide a value which represents the concentration of Ba^{2+} . (i.e. $2\text{A} - 2\text{B} = [\text{Ba}^{2+}]$ or ligand 2D).

30 The chemical structure of further examples of ligands are shown in figures 3 and 4. The indices n and m of the ligand in figure 3 can be 1 or 2. Figure 5 shows the example of a cryptand modified with a redox active

moiety. The entity M can be selected from a group consisting of Fe, Ru, Co, V, Cr, Mo, and W and n and m can range from 1 to 3.

5 In figure 6 there is shown the response of the ligand of figure 5 with M=Fe and n=m=2 to the presence of Ba²⁺. The solid line 51 is the typical electrochemical response of the pure ligand, whereas the dashed line 52 is the same response in the presence of Ba cations. The ligand of
10 figure 5 is sensitive to more than one species of scale-forming ions and the presence of different ions can be readily detected from determining the peak locations in the voltogramm. This ligand thus alleviates the need to use multiple ligands. Square wave voltammetry may be used
15 instead of the shown full cycle voltammetry.

The flowchart of figure 7 summarizes steps of a method exemplary of the present invention, including the step 71 of contacting a sample of for example downhole water with
20 a ligand which selectively binds scaling ions, the step 72 of measuring changes in the electronic configuration of the ligand, and the step 73 of determining the concentration of the scaling ions from the change in electronic configuration. The results of the measurement
25 may be fed into a model 74 that predicts the built-up of scaling in tubulars and other flow exposed equipment, for example production tubing or downhole pumps.

An application of the sensor is illustrated in figure 8.
30 It shows a Venturi-type flowmeter 810, as well known in the industry and described for example in the United States Patent No. 5,736,650. Mounted on production tubing or casing 812, the flowmeter is installed at a location within the well 811 with a wired connection 813 to the

surface following known procedures as disclosed for example in the United States Patent No. 5,829,520.

5 The flowmeter consists essentially of a constriction or throat **814** and two pressure taps **818**, **819** located conventionally at the entrance and the position of maximum constriction, respectively. Usually the Venturi flowmeter is combined with a densiometer **815** located further up- or downstream.

10

The novel scale sensor **816** is preferably located downstream from the Venturi to take advantage of the mixing effect the Venturi has on the flow. A recess **817** protected by a metal mesh provides an inlet to the unit.

15

During production wellbore fluid enters the recess **817** and is subsequently analyzed using sensor unit **816**. The results are transmitted from the data acquisition unit to the surface via wires **813**.

20

While the invention has been described in conjunction with the exemplary embodiments described above, many equivalent modifications and variations will be apparent to those skilled in the art when given this disclosure.

25 Accordingly, the exemplary embodiments of the invention set forth above are considered to be illustrative and not limiting. Various changes to the described embodiments may be made without departing from the spirit and scope of the invention.

30